DEVELOPMENT OF SOLID ROCKET PROPELLANT

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ABSTRACT

This thesis presents a study on development of solid rocket propellant that was carried out at Universiti Malaysia Pahang. Rocket propellant has been identified as a component that played an important role in the development of rockets. The ejected material in rocket propulsion is due to material called propellant. Without propellant, a rocket cannot be launched. A solid rocket is a class of rocket in which the fuel, oxidizer and binder are mixed together and cast into a solid material. Objective of this thesis is to produce potassium nitrate sucrose based solid rocket propellant. Materials used to produce this propellant are potassium nitrate powder and sucrose powder. Potassium nitrate is an oxidizer in the propellant material and sucrose as a fuel in the propellant. This propellant is produce using the method of formation. This method was easy to operate and cost effective. Burning rate test was carried out at 1 atm and 7 atm pressure using a different oxidizer/fuel mass ratio. At 1 atm pressure, it was found that burning rate for the ratio of 65/35 was 2.184 mm/sec. At 7 atm, it was found that burning rate for the ratio 65/35 was 3.791 mm/sec. Propellant must be kept in a cool dry place like it in the refrigerator to prevent it become melt. From the result of this research, the burning rate test rig has been successfully designed, fabricated and tested. As a conclusion, oxidizer / fuel ratio and combustion pressure influence burning rate test.

ABSTRAK

Tesis ini membentangkan kajian mengenai pembuatan propelan roket pepejal yang telah dijalankan di Universiti Malaysia Pahang. Roket propelan telah dikenal pasti sebagai komponen yang memainkan peranan penting dalam pembangunan roket. Bahan api yang keluar dalam pendorongan roket adalah disebabkan oleh bahan yang dikenali sebagai propelan. Tanpa dorongan, roket tidak boleh dilancarkan. Sebuah roket pepejal adalah kelas roket di mana bahan api, pengoksida dan pengikat dicampurkan bersama dan dibentuk menjadi bahan pepejal. Objektif tesis ini adalah untuk menghasilkan kalium nitrat sukros berasaskan propelan roket pepejal. Bahan yang digunakan untuk menghasilkan propelan ini adalah serbuk kalium nitrat dan serbuk sukros. Kalium nitrat merupakan pengoksida dalam propelan dan sukros sebagai bahan api dalam propelan. Propelan ini dihasilkan dengan menggunakan kaedah pembentukan. Kaedah ini adalah kaedah yang mudah untuk dikendalikan dan kos pembuatan yang murah. Ujian kadar pembakaran telah dijalankan pada tekanan 1 atm dan 7 atm dengan menggunakan bahan pengoksida/bahan api yang berbeza jisim nisbah. Pada tekanan 1 atm, didapati bahawa kadar pembakaran bagi nisbah 65/35 ialah 2.184 mm/sec. Pada tekanan 7 atm, didapati kadar pembakaran bagi nisbah 65/35 ialah 3.791 mm/sec. Daripada keputusan ujian yang telah dijalankan, kadar pembakaran telah dipengaruhi oleh nisbah pengoksida/bahan api dan ruang tekanan. Dalam menjalankan ujian kadar pembakaran, tempat yang paling sesuai ialah tempat yang tertutup dan mempunyai pengaliran udara yang baik. Propelan juga mesti disimpan di tempat kering dan sejuk seperti di dalam peti sejuk untuk mengelakkan menjadi cair dan terdedah kepada udara. Daripada hasil kajian ini, rig ujian kadar pembakaran telah berjaya direkabentuk, difabrikasi dan diuji. Kesimpulannya, pengoksida/bahan api dan pembakaran tekanan mempengaruhi kadar pembakaran.

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LIST OF SYMBOLS

a_{ij}	The number of atoms of element in the molecular formula
A	Propellant burning rate surface area
C_P	Specific heat
C_v	Specific heat of constant volume
ΔH_a	Product gas enthalpy
$\Delta_r H$	Free energy
$\bar{k}$	Ratio of specific heat of the gas mixture and liquids
k_{gas}	Product gas specific heat ratio
L	Propellant strip length
mol_R	Moles of species
m_s	Mass of species
M_S	Molecular weight species
$\dot{m}$	Mass flow rate
n	Number of species
n_j	Mole of molecular in a balanced chemical reaction equation
η_i	Moles of species
r	Burning rate
R_0	Universal gas constant
t_b	Burning rate for the strip
T_1	Final sintering temperature
T_{ref}	Reference temperature

LIST OF ABBREVIATIONS

C	Carbon
$C_{12}H_{22}O_{11}$	Sucrose
CH_4	Methane
CHEM	Chemical inventory software
CO_2	Carbon dioxide
H	Hydrogen (atom)
H_2	Hydrogen
H_2O	Water
K_2CO_3	Potassium carbonate
KNO_3	Potassium nitrate
N	Nitrogen
N_2	Nitrogen
NH_3	Ammonia
O_2	Oxygen
O/F	Oxidizer to fuel mixture ratio

CHAPTER 1

INTRODUCTION

1.1 Introduction

Rocket propellant has been identified as a component that played an important role in the development of rockets. The ejected material in rocket propulsion is due to a material called propellant. Without propellant, a rocket cannot be launched. A solid rocket is a class of rocket in which the fuel, oxidizer and binder are mixed together and cast into a solid material. A fuel propellant is often burned with an oxidizer propellant to produce large volumes of very hot gas. These gases are expand and push through a nozzle at extremely high speed and making thrust.

Under room temperature conditions, the propellant does not self-ignited except they were exposed to an external source of heat. Once the burning starts, it will proceed until all the propellant is burned and hot exhaust gases is produced which is used to propel the rocket.

The principal advantage is that a solid propellant is relatively stable, therefore it can be manufactured and stored for future use. Solid propellants have a high density and can burn very fast. They are relatively insensitive to shock, vibration and acceleration. No propellant pumps are required thus the rocket engines are less complicated.

Disadvantages of solid propellant are they cannot be throttled turned off or restarted once they were ignited. The surface area of the burning propellant is critical in determining the amount of thrust being generated. Cracks in the solid propellant increase the exposed surface area thus the propellant burns faster than planned.

Many solid rocket propellant engines feature a hollow core that runs through the propellant. Rockets that do not have the hollow core must be ignited at the lower end of the propellants and will gradually burn from one end to the other. However, for certain application the hollow core is used due to their higher surface area for burning. Some propellant cores are star shaped to increase the burning surface even more.

1.2 Problem Statement

In this project, there are some problem statement including data related to solid rocket propellant is too less in order to serve as a reference guide of funds. The other hand data on the burning rate test rig potassium nitrate sucrose are also difficult to find. So, in this project, there are a few expected works to do on potassium nitrate sucrose based solid propellant. The test rig needs to be designed especially burning rate test rig. The analysis includes specific impulse of the propellant and the burning rate of the propellant.

1.3 Objective

To produce potassium nitrate sucrose based solid rocket propellant.

1.4 Scope of project

There are four scopes in this study:

(i) Fixed parameter pressure at 1 atm and 7 atm.
(ii) Stoichiometric ratio analysis.
(iii) Construction potassium nitrate sucrose propellant
(iv) Construction of strand burner.

1.5 Project Methodology

The research methodology in the form of a flow chart is graphically shown in Figure 1.1.

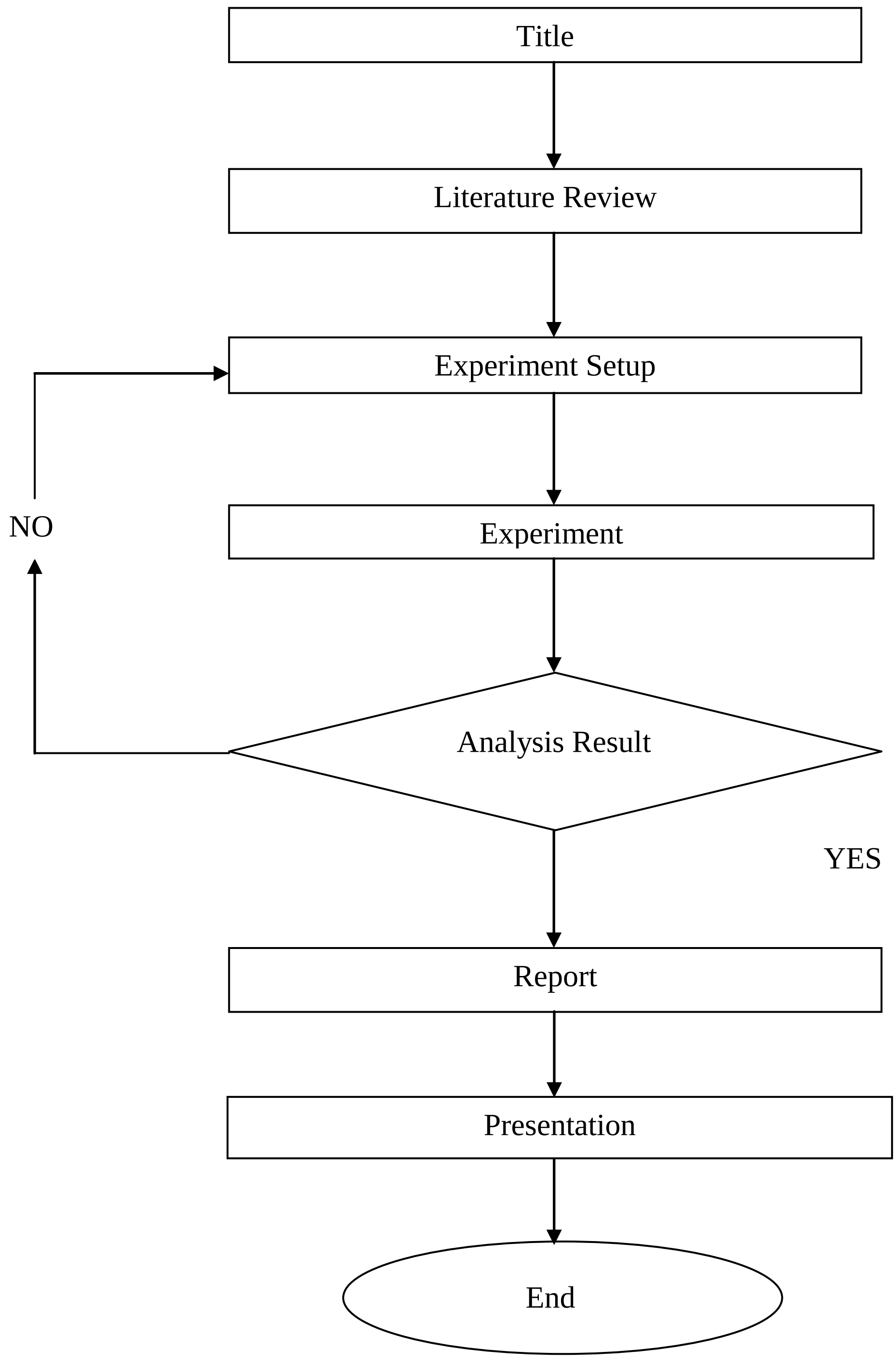

Figure 1.1: Flow chart

1.6 Outline of Report

The report in this study is divided into five chapters. Chapter 1 provides the general introduction on the study and it include the objective, scopes, project methodology and outline report of the study.

Chapter 2 presents literature reviews on solid rocket propellants. The reviews start with the history and development of rocket technology around the world. Then, discussion of the solid rocket propellant in detail. This chapter also described the ingredient and property of the rocket propellant that needs to be studied.

Chapter 3 discuss the methodology of this project. From this methodology, the first thing discusses is related to assumption for ideal rocket motor that will facilitate the analysis related to rocket motor. After that, the fabrication process to make the propellant and facilities setup briefly explained. Then, discussions on the analysis of burning rate and property's analysis also discussed in this chapter. The discussion be discussed include a detailed description and importance formula.

Chapter 4 discuss the methods used to produce the best results in this studying including construction of burning rate test rig and experimental work. This chapter also show result obtained using the chemical inventory software (CHEM). All results and analysis of the solid rocket propellant will be described in this chapter.

Chapter 5 presents conclusion and recommendation from this study. This chapter describe in detail the results obtained by experiment that was carried out and conclude the result. Then, future research in this study will be discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will discuss related matters especially about solid rocket propellant. After that, the analysis related to solid rocket propellant used will be discussed in this chapter as well. Then, discussion on basic ingredients that commonly used in composite solid propellants was covered and also at the end of this chapter will be discussed about the strand burner and propellant grain.

2.2 History of Solid Rocket Propellant

In the first century A.D, the Chinese reportedly had a simple form of gunpowder made from saltpetre, sulphur and charcoal dust [Source: J.D.Hunkey et.all]. In order to create explosions during religious festivals, they filled bamboo tubes with a mixture and tossed them into fires. Perhaps some of those tubes failed to explode and instead skittered out of the fires, propelled by the gases and sparks produced by the burning gun powder. The Chinese began experimenting with the gunpowder-filled tubes. At some point, they attached bamboo tubes to arrows and launched them with bows. Soon they discovered that these gunpowder tubes could launch themselves just by the power produced from the escaping gas.

During the latter part of the 17th century, the scientific foundations for modern rocketry were laid by the great English scientist Sir Isaac Newton (1642-1727) [Source: Roger E.Lo]. Newton organized his understanding of physical motion into three scientific laws. The laws explain how rockets work and why they are able to work in the vacuum of outer space. Newton's laws soon began to have a practical impact on the design of rockets. About 1720, a Dutch professor, Willem Gravesande, built model cars propelled by jets of steam [Source: Roger E. Lo].

Goddard's earliest experiments were with solid-propellant rockets. In 1915, he began to try various types of solid fuels and to measure the exhaust velocities of the burning gases [Source: Robert Goddart]. While working on solid-propellant rockets, Goddard became convinced that a rocket could be propelled better by liquid fuel. No one had ever built a successful liquid-propellant rocket before. It was a much more difficult task than building solid- propellant rockets. Fuel and oxygen tanks, turbines, and combustion chambers would be needed. In spite of the difficulties, Goddard achieved the first successful flight with a liquid- propellant rocket on March 16, 1926 [Source: Robert Goddart]. By today's standards, the flight was unimpressive, but like the first powered airplane flight by the Wright brothers in 1903, Goddard's gasoline rocket was the forerunner of a whole new era in rocket flight. Goddard's experiments in liquid-propellant rockets continued for many years. His rockets became bigger and flew higher. He developed a gyroscope system for flight control and a payload compartment for scientific instruments. Parachute recovery systems were employed to return rockets and instruments safely. Goddard, for his achievements, has been called the father of modern rocketry.

2.3 Development of Solid Rocket Propellant

The development of solid rocket at UMP can be divided into two stages. The first stage is the development of the solid propellant. At UMP, potassium nitrate was used due to the ease of availability and fabrication. The second stage involves the development of the solid propellant performance test rig. These include the burning test rig.

2.4 Propellant Ingredients and Properties

In this project, there is one type of propellant that must be produced using one types of oxidizer that is potassium nitrate. The propellant will contain ingredients of fuel, oxidizer and binder. With a mixture of all three of these ingredients, propellant will produce according to the procedures specified.

2.4.1 Fuel

The first ingredient in solid propellant was fuel. Fuels used in this project are sucrose. Sucrose, the technical name for table sugar, cane sugar, or white sugar is made of one glucose molecule and one fructose molecule bound together. It comes in powdered and granulated forms, sugar is made from highly processed form of sugar beet or sugar cane plant extracts. Sucrose, ordinary table sugar, is probably the single most abundant pure organic chemical in the world and the one most widely known to nonchemists.

Sucrose is the organic compound commonly known as table sugar. A white, odourless, crystalline powder with a sweet taste, it is best known for its nutritional role. The molecules are a disaccharide composed of the monosaccharides glucose and fructose with the molecular formula $C_{12}H_{22}O_{11}$.

Sucrose used in this project can acts as a binder material and fuel. Sucrose used was from a local product that is in another language is sugar. This will be a fine-grained sugar before being used in making the propellant. Sucrose classified as carbonate organic matter and very dangerous when mixed with potassium nitrate. Therefore, the equipment used to prepare potassium nitrate and sucrose should be separate to avoid mixing of this materials.

2.4.2 Oxidizer

Second ingredient is oxidizers which supply oxidizing materials for combustion process of a solid propellant. The main oxidizer used in this project is potassium nitrate. These types of oxidizer will be discussed further and in detail and the functions of this oxidizer in solid propellant is also to be discussed.

Potassium nitrate is a chemical compound with the formula KNO_3. It is an ionic salt of potassium ions K^+ and nitrate ions NO_3^-. It occurs as a mineral niter and is a natural solid source of nitrogen. Potassium nitrate is a transparent, colourless-to-white crystalline powder or crystals with a cooling, pungent, saline taste. It is soluble in water and slightly soluble in alcohol and glycerine. Potassium nitrate is one of several nitrogen that is containing compounds collectively referred to as saltpetre. Major uses of potassium nitrate are in fertilizers, food additive, rocket propellants and fireworks; it is one of the constituents of gunpowder [Source: Martin J.L.T].

Potassium nitrate is a powerful oxidizing agent which is used in pyrotechnics, explosives, matches, fertilizers, metallurgy, analytical, chemistry and preparation of medicines [Source: Boris Kit et.all]. In rocket technology it is used as an oxidizer in solid propellant grains [Source: Boris Kit et.all]. Potassium nitrate is also known as saltpetre. This material is the initial propellant that has been used for the rocket engine propulsion system. Potassium nitrate is the fuel that is classified as low explosives [Source: Martin J.L.T], where they bring their own materials for the oxidation of it was burned but did not explode. Not as a substance which is classified as a high explosive materials such as a strinitrotoloen, dynamit, tetryl and ammonium perchlorate are not as fuel. However, most of these materials ignited using the flame or heat. If the material is heated from the inside it will explode.

Fabrication of a propellant that contains a powerful oxidizer such as potassium nitrate is very dangerous and could cause an explosion. Potassium nitrate should be stored in a cool, enclosed in an airtight container at a safe distance from easily oxidizable organic and other materials. Ammonium nitrate also presents problems of toxicity. Ingestion may cause methemoglobinemia. As an oxidizer, potassium nitrate does not give a very high specific impulse. However, it is very inexpensive and easily available and it produces complete, smokeless and nontoxic combustion [Source: Boris Kit et.all]. Potassium nitrate has been used as a component of both smokeless powders and rocket propellants [Source: Rizalman M].

2.5 Strand Burner (Crawford Bomb)

A strand burner or also known Crawford burner is a device used to test burning rate of solid propellant. A strand burner consists of a small pressure vessel in which a thin bar of propellant to be tested is mounted on a mounting strand. The bar is coated with an external coating so that burning cross-sectional surface is restricted [Source: Kubota]. The propellant is ignited at one end and burned to the other end. Wires are embedded in the propellant at certain intervals of distance so that when the propellant burning reaches the wires, electric signals are sent through the wire. These wires are connected to a timer and the electrical signals are recorded at different time intervals so that burning rate can be measured. Nevertheless, the strand burner experiment is easy to perform, can be repeated and a qualities picture of the burning rate is obtained. The temperature sensitivity of burning rate is usually calculated from strand burner test data.

Burning rate of the propellant is one of the important parameters for the of rocket motors design. Function of pressure, initial temperature, and pressure exponent of burning rate and temperature sensitivity of burning rate is deduced through the propellant burning rate test. Figure 2.1 shows drawing of a strand burner pressurized to the desired pressure.

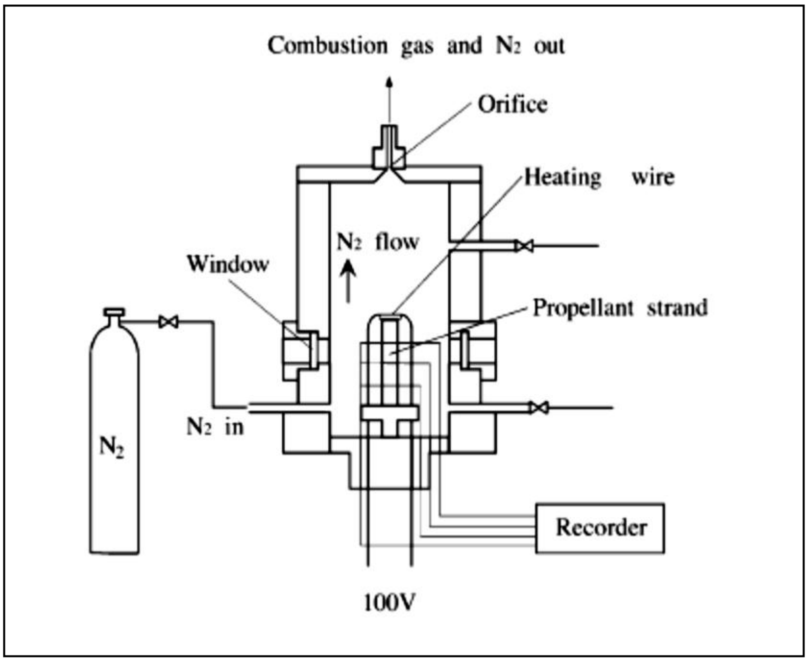

Figure 2.1: A chimney-type strand burner with observation window

[Source: Kubota]

The pressure in the strand burner increases when a propellant strand is ignited because of the addition of the propellant burned gas and the increasing of the temperature. However, in order to maintain the pressure constant, the pressure valve was strand burner and commonly it will regulate automatically to reduce the gas flow rate. Thus, the pressure in the burner is maintained at the desired pressure [Source: Kubota].

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discuss the methodology of this project. In this methodology, the first thing discusses is related to assumption for ideal rocket motor that will facilitate the analysis related to rocket motor. Then, discussions on the analysis of burning rate and combustion analysis. The discussion will be discussed will include a detailed description and importance formula. After that, the fabrication to make the propellant will show in this chapter and also including the facilities setup.

3.2 Assumption for Ideal Rocket Motor

For chemical rocket propulsion the measured actual performance is usually between 1% and 6% below the calculated idea value [Source: George P.Sutton]. An ideal rocket unit is one for which the following assumptions are valid [Source: George P.Sutton]:

(i) The working substance or propellant combustion is homogeneous.
(ii) All working fluid are gaseous. Any condensed phases add a negligible amount to total mass.
(iii) Combustion products obey perfect gas law
(iv) Flow is adiabatic. No heat transfer cross the nozzle wall
(v) There is no friction. All boundary layer effect is negligible
(vi) No shock waves in the nozzle
(vii) Propellant flow is steady and constant. The expansion of the working fluid is uniform and steady without vibration
(viii) Gas velocity, pressure, temperature, and density are all uniform across any section normal to the nozzle axis
(ix) All exhaust gases leaving the rocket have an axially directed velocity

3.3 Analysis of Burning Rate

The burning rate is a measure of the linear combustion rate of a compound or substance such as a candle or a solid propellant. Burn rate is measured in length over time, such as "mm/second" or "inches/second". Burn rate is a property of combustible substance and it quantifies the combustion rates. Burning rates can be measured and are different for a given substance at different pressures. Burning rate typically increases with pressure and temperature.

3.3.1 Propellant burning rate

The burning propellant surface that is perpendicular to it surface is measured by calculating the rate of propellant to burn. Usually it is measured in units of distance per unit time as in equation (3.1).

With

$$r = L / t_b \tag{3.1}$$

r = burning rate

L = propellant strip length

t_b= burning time for the strip

3.3.2 Mass Flow Rate

Mass flow rate is defined as the ratio of mass flow through a given point on a unit time. For rocket motor cases, the mass flow is the result of burning propellant. Therefore this equation can be written as in equation (3.2).

$$\dot{m} = \rho_p A r \tag{3.2}$$

Where,

r = burning rate

A = propellant burning surface area

ρ_p = density of propellant

$\dot{m}$ = mass flow rate

3.4 Propellant Combustion Analysis

Analysis of combustion in rocket motor cases need to consider before and after combustion. This is consistent with the First Law of Thermodynamics which says energy cannot be created or destroyed or in other word energy is permanent except the atomic reaction, it can only be changed from one form of energy to other form of energy. When the rocket motors operate, the chemical energy stored in the propellant converted to heat energy and after that to the kinetic energy. The gas is accelerated through the nozzle and generates momentum in the rocket motor.